

PLANETARY ORIGIN, EVOLUTION AND STRUCTURE

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Here are three areas of recent and ongoing research under this general title:

Giant Planet Heatflows

Conventional wisdom¹ attributes the heatflow of the giant planets to the gradual loss of primordial heat, except in the case of Saturn where helium separation is evidently occurring.² There are two problems with this picture: (1) The observed helium abundance of Saturn's atmosphere is so low³ that Jupiter must also be differentiating helium since its internal entropy cannot be much higher than Saturn; (2) The heatflow of *Neptune* (not to mention *Uranus*) is too high to be consistent with adiabatic cooling from an initial hot state.

I believe that I have a self-consistent solution to these difficulties. In the case of Jupiter and Saturn, my cooling models yield the correct present-day heatflows and present-day atmospheric helium abundances for both planets, but only if both planets have an innermost region (~30% of the mass) that does not participate in the cooling. In the case of Jupiter, this cannot be a core of ice and rock (since it is too large) but must be a region of stable stratification, presumably created by the partial mixing and imperfect settling that occurs during the accretion of large ice and rock planetesimals early in Jupiter's history. The stably stratified region must have a substantial molecular weight gradient, yet is thermally superadiabatic. In effect, this model denies the validity of the simple, adiabatic cooling for Jupiter even though that model yields the correct heatflow. The implication of stable stratification is consistent with ideas of planetary accretion.⁴ The Jupiter model will be testable by the Galileo probe.

In the case of *Uranus* and *Neptune*, stable stratification is even more important and is predicted to be larger for *Uranus* than for *Neptune*. This is compatible with but not readily tested by interior models based solely on the gravity field.⁵ The necessary presence of large, stably stratified zones in these planets is probably essential to an understanding of their unusual magnetic fields.

Despinning Protogiant Planets

There are two views of giant planet accretion. In the best quantified view,⁶ protoJupiter or protoSaturn fills much of its Hill sphere and then cools and contracts, leaving behind a disk of material from which the satellite system forms. An alternative view envisages an accretion disk even as gas accumulation continues; this is analogous to the standard picture of solar system formation⁷ and arises if the dust opacity is low because of aggregation into "large" bodies (centimeters is large enough). In either case, there is certain to be a late phase in which the protogiant planet is surrounded by a disk of material with which it interacts through "viscous" torques, inflow, and outflow. In these circumstances, it is not possible for the protoplanet to exhibit a surface rotation rate very different than rotational break-up.^{8,9} For reasonable moments of inertia, this implies an angular momentum substantially larger (typically by a factor of two) than currently observed for Jupiter and Saturn. This is a fundamental problem in the spin of giant planets.

Graduate student Toshiko Takata and I have been modeling the possible despinning of these protoplanets by hydromagnetic torques. Our model has some similarity with stellar despinning models.^{10,11} The main idea of the model is exhibited in Figure 1, which shows that angular momentum is transferred from the protoplanet to the disk at all radii beyond corotation because of the coupling of planetary dipole field lines to the disk fluid and the resulting current and Lorentz force thereby created. We find that bombardment of high energy particles created by *Jupiter* and flowing along fieldlines is a potentially adequate source of ionization and conductivity. Figure 2 shows despin times (time to reach the current angular momentum) as a function of protoplanet surface magnetic field and for two choices of protoplanet radius and two choices of magnetic diffusivity. Our most optimistic diffusivity model yields $\lambda = 10^{14}$ cm²/s, but the solid lines ($\lambda = 10^{15}$ cm²/s) are probably more realistic. The dashed lines are a pessimistic case. All these models assume a disk of the kind believed appropriate for spawning the Galilean satellites.¹² This model is uncomfortably marginal but seems capable in principal of explaining the spin states of *Jupiter* and *Saturn*, provided both planets had large primordial fields.

How Titan Hides its Ocean

Until recent, the favored picture for *Titan*'s surface was a roughly kilometer-thick ethane/methane ocean,¹³ presumably global in extent with at most a few outcroppings of "dry" land. The depth of the ocean is well constrained (to within a factor of two) by observed atmospheric properties (presence of methane, escape of hydrogen) and the constraints on subaerial topography are obtained indirectly from tidal considerations.¹⁴

The only observational approach currently available for directly establishing the character of the surface is radar.¹⁵ They observe a radar albedo of ~ 0.35 , clearly incompatible with a global hydrocarbon ocean. I have been pursuing a different picture for *Titan*'s surface, partially motivated by ideas that Jon Lunine and I considered many years ago,¹⁶ but primarily motivated by the perspective that methane on *Titan* should more properly be considered as a magmatic fluid. In this picture, methane is stored subsurface in "magma chambers" fed from deep-seated (perhaps very ancient) sources of methane, most probably due to the high pressure breakdown of methane clathrate, as previously suggested.¹⁷ I show that magma chambers of methane tend to sink because of the temperature and pressure-dependent solubility of water in methane; this can balance the tendency to rise because of buoyancy. A natural "perching level" for these chambers is predicted, typically ten or so kilometers beneath *Titan*'s surface for kilometer-sized diapirs. From this level, a labyrinth of cracks and caverns could connect to the surface, providing a continuous source of methane for the atmosphere. Only a few square meters of opening between deep storage and the atmosphere is needed to maintain chemical and vapor pressure equilibria between these reservoirs. The model is compatible with tidal dissipation provided the subsurface hydrocarbon liquid is *not* globally interconnected by large aperture ("rapid transit") tunnels. The model is most plausible for methane supplied from below but may even work for methane supplied from above (and seeping downward).

Acknowledgement

This work was supported by NASA under grant NAGW-185.

References

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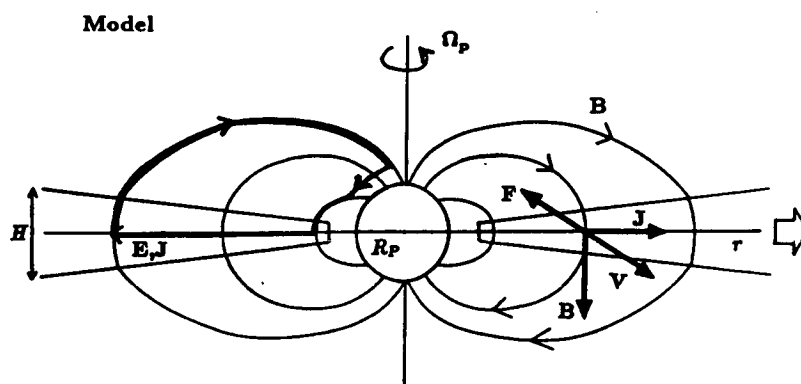


Figure 1. Model for a hydromagnetically coupled disk and protogiant planet.

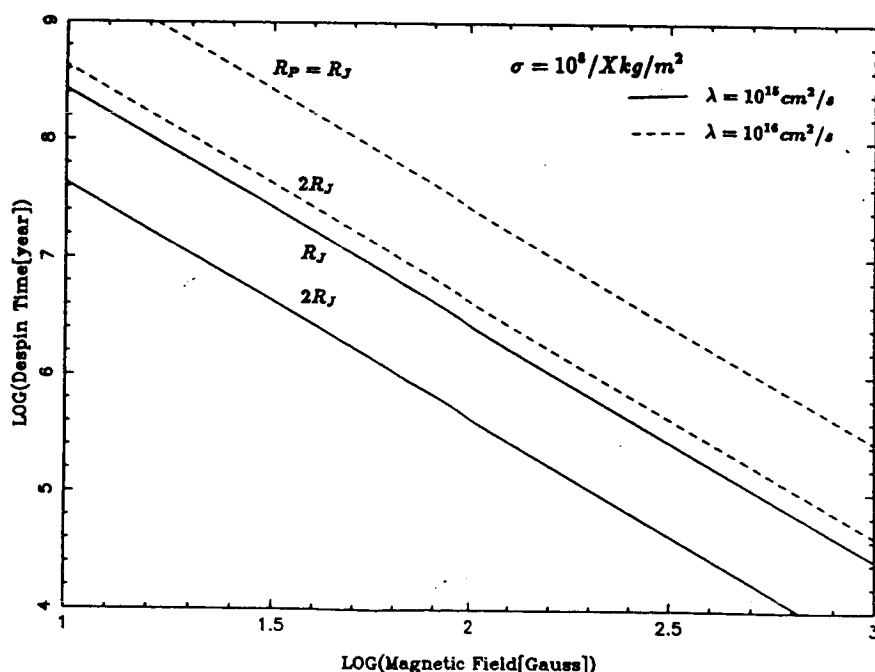


Figure 2. Despin time (time to reduce spin angular momentum of the giant planet to its current value) as a function of planetary surface magnetic field.